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SOME ASPECTS OF THE THEORY OF TURBULENCE

BY E. J. SUMNER, B.A.

Part III

Up to now we have confined our ideas to a fairly realistic picture of atmospheric motion, and have tried to define our concepts in relation to it. Sooner or later, however, theoretical results have to be compared with actual measurements, and it is necessary to put one's theories in a form suited to such a comparison. This often entails drastic assumptions and incomplete formulations, and the precise physical significance of the steps involved is almost invariably lost sight of. But the experience is normally a salutary one provided the assumptions made are clearly stated. The remainder of this article gives a brief outline of a few past attempts at conjoining theory with practice. It follows on from the fundamental equation $\partial\bar{\theta}/\partial t = -\partial(\overline{w'\theta'})/\partial z$, deduced in Part I, and deals with its resolution in terms of mixing-length concepts. The first few paragraphs are by way of a digression in order to provide us with sufficient background to understand current terminology and to appreciate subsequent advances.

The presiding genius in the dynamical theory of turbulence is Osborne Reynolds, who laid the foundation of modern developments in a classical paper published in 1894.[1]* He considered the terms to be introduced into the equations of mean motion in order to allow for the presence of the eddy velocities (defined earlier), and in view of their importance it would be as well to give them in full.† The equations of mean motion on the earth's surface are:—

$$\rho\frac{D\bar{u}}{Dt}+2\rho\omega(\bar{w}\cos\phi-\bar{v}\sin\phi)=-\frac{\partial\bar{p}}{\partial x}-\frac{\partial}{\partial x}(\rho\overline{u'u'})-\frac{\partial}{\partial y}(\rho\overline{u'v'})-\frac{\partial}{\partial z}(\rho\overline{u'w'})+\mu\nabla^2\bar{u} \quad (7)$$

$$\rho\frac{D\bar{v}}{Dt}+2\rho\omega\bar{u}\sin\phi=-\frac{\partial\bar{p}}{\partial y}-\frac{\partial}{\partial x}(\rho\overline{v'u'})-\frac{\partial}{\partial y}(\rho\overline{v'v'})-\frac{\partial}{\partial z}(\rho\overline{v'w'})+\mu\nabla^2\bar{v} \quad (8)$$

$$\rho\frac{D\bar{w}}{Dt}-2\rho\omega\bar{u}\cos\phi=-\rho g-\frac{\partial\bar{p}}{\partial z}-\frac{\partial}{\partial x}(\rho\overline{w'u'})-\frac{\partial}{\partial y}(\rho\overline{w'v'})-\frac{\partial}{\partial z}(\rho\overline{w'w'})+\mu\nabla^2\bar{w} \quad (9)$$

in which $\bar{u}$, $\bar{v}$, $\bar{w}$ are the components of mean velocity along mutually per-

* These numbers refer to the list of references on p. 128.

† For the derivation of equations (7)–(9) see Brunt's "Physical and dynamical meteorology".

pendicular coordinate axes OX, OY, OZ (drawn horizontally to the east, horizontally to the north, and vertically, respectively), u', v', w' are the corresponding eddy velocities, p the atmosphere pressure, ρ the air density, ω the angular velocity of rotation of the earth about its axis, ϕ the latitude, and μ the coefficient of molecular viscosity of air. The symbol D/Dt represents differentiation following the mean motion and ∇^2 is the normal Laplacian operator. Thus we have the following identities:—

$$\frac{D}{Dt}=\frac{\partial}{\partial t}+\bar{u}\frac{\partial}{\partial x}+\bar{v}\frac{\partial}{\partial y}+\bar{w}\frac{\partial}{\partial z}$$

and $$\nabla^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}.$$

The terms involving ω and ϕ are the familiar Coriolis forces due to the earth's rotation. By analogy with the molecular shear stresses $\mu\partial\bar{u}/\partial x$, $\mu\partial\bar{v}/\partial y$, etc., the characteristic parameters $-\rho\overline{u'u'}$, $-\rho\overline{u'v'}$, etc., were called "eddy" shear stresses, and are often written τ_{xx}, τ_{xy}, etc. In these equations a bar over a particular symbol implies a mean value with respect to time. They only apply to an incompressible fluid, and may be simplified further by neglecting molecular viscosity by comparison with eddy viscosity. Assuming also that there is no mean vertical velocity ($\bar{w}=0$) and ignoring all horizontal gradients (i.e. all terms involving the operators $\partial/\partial x$ and $\partial/\partial y$) except those of pressure, the equations reduce to

$$\frac{\partial u}{\partial t}-2\,\omega\,\bar{v}\sin\phi=-\frac{1}{\rho}\,\frac{\partial\bar{p}}{\partial x}+\frac{1}{\rho}\,\frac{\partial\tau_{xz}}{\partial z} \qquad ..\ (10)$$

$$\frac{\partial v}{\partial t}+2\,\omega\,\bar{u}\sin\phi=-\frac{1}{\rho}\,\frac{\partial\bar{p}}{\partial y}+\frac{1}{\rho}\,\frac{\partial\tau_{yz}}{\partial z} \qquad ..\ (11)$$

$$-2\,\omega\,\bar{u}\cos\phi=-g-\frac{1}{\rho}\,\frac{\partial\bar{p}}{\partial z}+\frac{1}{\rho}\,\frac{\partial\tau_{zz}}{\partial z} \qquad ..\ (12)$$

If U, V are the horizontal components of the geostrophic wind, neglecting vertical variation of the horizontal pressure gradient within the friction layer,

then $$2\,\omega\,V\sin\phi=\frac{1}{\rho}\,\frac{\partial\bar{p}}{\partial x}$$

and $$-2\,\omega\,U\sin\phi=\frac{1}{\rho}\,\frac{\partial\bar{p}}{\partial y}$$

and substituting in equations (10) and (11) we obtain

$$\frac{\partial\bar{u}}{\partial t}+2\,\omega\,(V-\bar{v})\sin\phi=\frac{1}{\rho}\,\frac{\partial\tau_{xz}}{\partial z} \qquad ..\ (13)$$

$$\frac{\partial\bar{v}}{\partial t}-2\,\omega\,(U-\bar{u})\sin\phi=\frac{1}{\rho}\,\frac{\partial\tau_{yz}}{\partial z} \qquad ..\ (14)$$

It will be noticed that if we ignore the change of wind with height in the lowest layers of air, and take our x-axis parallel to the direction of the mean wind (i.e. $\bar{v}=V=0$), equation (13) becomes

$$\frac{\partial\bar{u}}{\partial t}=\frac{\partial\tau_{xz}}{\partial z}=-\frac{\partial}{\partial z}(\overline{u'w'}), \qquad ..\ (15)$$

which is the two-dimensional equation previously arrived at in Part I for

momentum transfer, making the same assumptions. A more accurate expression can be got from (10); by re-orientating the axes as before ($\bar{v} = 0$), we have

$$\rho \frac{\partial \bar{u}}{\partial t} = - \frac{\partial \bar{p}}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} \quad .. (16)$$

which includes the pressure gradient along the direction of the mean motion at a particular level, and it is a moot point as to whether or not this term may invariably be neglected by comparison with the others. Strictly speaking equation (15) only represents the changes in the mean velocity due to the eddy stresses. Insofar as the horizontal pressure gradient is more or less constant in the lowest few metres of the atmosphere, and since there is usually no observable wind-direction change with height, the effect of the factor is to accelerate the air bodily, whereas the last term in equation (16) produces differences of velocity with height. We are thus enabled to separate the two in practice by dealing with differences of velocity from a standard height rather than absolute values.

The above equations will be referred to again later; meanwhile one example of terminology is of interest. Consider the parameter $-\rho\overline{u'w'}$; since it is of the nature of a shear stress, we may write

$$-\rho\,\overline{u'w'} = \tau_{xz} = \rho K \frac{\partial \bar{u}}{\partial z} \quad .. (17)$$

by analogy with molecular viscosity in laminar flow, where K is called the coefficient of eddy viscosity.

Practical application.—The idea of mixing length was first introduced by Taylor in England, and independently by Prandtl in Germany, although it was the latter who built a consistent theory around it. He was concerned only with momentum transfer and, in this case, the problem is to find a way of expressing $-\rho\overline{u'w'}$ in terms of measurable quantities. As we have seen $u' = l_1 \partial\bar{u}/\partial z$, l_1 being the so-called *Mischungsweg* or mixing length, and assuming w' to be of the same form, $\pm l_2 \partial\bar{u}/\partial z$, say, the eddy shearing stress may be written

$$\tau = -\rho\,\overline{u'w'} = \pm\,\rho\,l_1\,l_2 \left(\frac{\partial \bar{u}}{\partial z}\right)^2 = \pm\,\rho\,l^2 \left(\frac{\partial \bar{u}}{\partial z}\right)^2,$$

where $l^2 = l_1\,l_2$. If the mean velocity increases with height it is obvious that when w' is positive u' must be negative and *vice versa* so that to have the correct sign the above equation becomes

$$\tau = \rho\,l^2 \left|\frac{\partial \bar{u}}{\partial z}\right| \frac{\partial \bar{u}}{\partial z}, \quad .. (18)$$

where $|\partial\bar{u}/\partial z|$ is the absolute value of the mean gradient. From (17), substituting for τ (the suffixes are dropped for convenience) we have

$$K = l^2 \left|\frac{\partial \bar{u}}{\partial z}\right|. \quad .. (19)$$

These two equations are the principle links in the theory; l is now simply a quantity with the dimensions of a length and only roughly corresponds to previous specifications. The next step is to determine the dependence of l on other factors. Von Kármán[2], on the hypothesis that turbulence, apart

from scale, is geometrically similar throughout the field of flow (the principle of dynamical similarity) deduced that

$$l = k_0 \left| \frac{\partial \bar{u}}{\partial z} \right| \Big/ \left| \frac{\partial^2 \bar{u}}{\partial z^2} \right|, \qquad \ldots (20)$$

where k_0 is a dimensional constant. Its value was first measured by Nikuradse[3], in 1932, for the flow of water in cylindrical pipes, and was found to be about 0·4; it is apparently a universal parameter and does not depend on the Reynolds' number. Now it is by no means certain that the l in this equation is the same as that of the previous two; in fact it should be a very good representation of the transport length l of Part II, which depends entirely on the dynamics of the eddies, whereas that of equations (17) and (19) is more akin to the earlier ideas of mixing length, which we have called l_0. However, if we do assume l to be the same in all three equations and if, in addition, it is assumed that the eddy shearing stress is constant and equal to τ_0 (its value at the boundary), we may eliminate l from equations (18) and (20), and obtain the solution

$$\bar{u} = \frac{1}{k_0} \sqrt{\left(\frac{\tau_0}{\rho}\right)} \cdot \log \frac{z + z_0}{z_0}, \qquad \ldots (21)$$

as the law of variation of $\bar{u}$ with height, where z_0 is a constant of integration. This equation only holds for flow near to an aerodynamically rough surface, that is one above which turbulence is fully developed right down to it, and for which there is no slip at the boundary ($\bar{u} = 0$ when $z = 0$). The formula when substituted in (20) gives

$$l = k_0(z + z_0) \qquad \ldots (22)$$

All the above equations were first applied to laboratory experiments, for flow in tubes and wind tunnels, etc., and here z_0 is a roughness parameter. An equation of the form of (21) was shown to describe the velocity profile in a wide variety of circumstances in spite of the fact that the shear stress was known to vary with distance from the boundary, which led Thorade[4] to suggest that the variations in τ are possibly compensated by variations in l.

Because of the generality of the above concepts it was an easy step to attempt to apply them to the atmosphere, even in cases of wide departure from the isothermal conditions of the laboratory, and it is a remarkable fact that they do accord with our experience. Except in the cases of a plane sheet of water or a smooth expanse of ice with light winds, the earth's surface is always aerodynamically rough and equation (21) should apply provided τ is constant with height. Sutton[5], among others, has shown that a logarithmic law is a good approximation to wind profiles, measured under all conditions of thermal stability, in the lowest two metres of the atmosphere. His equation is of the form

$$\frac{\bar{u}}{\bar{u}_1} = \frac{\log(\alpha z/z_1 + 1)}{\log(\alpha + 1)} \qquad \ldots (23)$$

where $\bar{u}_1$ is the mean wind at a standard height, and α is a turbulence parameter which increases enormously with instability and depends to a less extent on the surface roughness. This formula is, of course, another form of equation (21), for which $z_1 = \alpha z_0$, so that z_0 is a function both of lapse rate and surface roughness. In the laboratory z_0 is a physical constant directly proportional to the average height of the surface-roughness elements, but in the atmosphere,

because the dependence of α on lapse rate, this is not so, and Sutton suggested that the surface roughness is much more influential in inversions (when α is small) than under unstable conditions. Sverdrup[6], however, while not refuting the idea, has taken the view that z_0 is an absolute constant for a particular surface, and showed that a better fit, in the unstable state at least, to Sutton's data could be obtained by slightly modifying the logarithmic formula by the addition of a term βz, where β replaces the turbulence parameter α. In inversions Sverdrup's equation is not so good. On the available evidence it is impossible to decide between the two formulæ especially as the fact of the constancy of eddy shear with height, on which they are based, may be disputed except in the steady state. Ertel[7], using equations (13) and (14) with $\partial\bar{u}/\partial t$ and $\partial\bar{v}/\partial t$ both equal to zero, showed that in this case one may ignore the variations of τ with height, at least in the lowest 30 m. of the atmosphere. His proof assumed that there is no change of wind direction with height over this range, and was for isotropic turbulence only. Calder[8] remedied the first defect and demonstrated that the small variations actually observed over this range had very little effect on Ertel's result. He also showed that, although the change of wind direction in the lower atmosphere is of no measurable significance (presumably for steady winds) a very small variation (of the order of 1°/100 m.) suffices to account for a large vertical velocity gradient. This work, of course, constitutes a justification for the use of the approximate equation (15) in the steady state, because here $\partial\bar{u}/\partial t$ and $\partial\tau/\partial z$ become zero together so that τ is necessarily constant with height.

Sheppard[9] actually measured the drag τ_0 of the wind on a concrete surface flush with the ground and, using equation (21), established that 0·4 was a reasonable value for k_0 in the atmosphere under isothermal conditions. He deduced from his own and Best's observations[10] that k_0 decreases with increasing stability, but the reality of these variations is by no means universally accepted, and the author himself remarked that the validity of the results depended on that of the equations used in their computation, and that Kármán's constant must be used with care in the lower atmosphere even when a value adjusted for stability is employed. Although a logarithmic profile is a good approximation to the mean-wind profile in the lowest 1–2 m., power laws are probably better in inversions over a much greater depth and are a good approximation in all stabilities for $z > 1$ m. Whichever law really applies, equation (18), in the form

$$l = \sqrt{\left(\frac{\tau_0}{\rho}\right)} \Big/ \left|\frac{\partial\bar{u}}{\partial z}\right|,$$

may be used to calculate the variation of mixing length with height. Sheppard's results suggested a linear relation for heights up to 1 m., but above that l increased more rapidly than the height for an unstable atmosphere, and probably less rapidly in inversions, as might have been expected. This statement, it must be emphasised, depends on the assumption that $\tau = \tau_0$ at all heights and under all circumstances, for which there is little factual evidence. The remarks about the variation of K_θ with height and stability in Part II are based on a similar hypothesis.

To utilise these equations for the diffusion of other properties—they were originally deduced for momentum transfer only—it is usual to equate the

three coefficients of eddy viscosity, eddy conductivity and eddy diffusivity. As we have seen there is good reason to doubt that their absolute magnitudes are equal, but there is some evidence that as far as their law of variation with height is concerned they are similar in form near the ground. The most important general theory, and one which makes this assumption, is perhaps that of O. G. Sutton[11] previously referred to. By a most ingenious combination of empiricism, statistics and mixing-length ideas, he extended the theory given in Part I as far as equation (1), and arrived at the partial-differential equation:

$$\frac{\partial\bar{\theta}}{\partial t} = \alpha_1 \frac{\partial}{\partial z}\left(z^{1-m}\frac{\partial\bar{\theta}}{\partial z}\right) \quad \text{.. (24)}$$

where θ is any property as before, and m, for meteorological purposes, is a function of the vertical temperature gradient and the roughness of the surface ($0 \leqslant m \leqslant 1$) while α_1 is a function of m and the kinematic viscosity of air. The dependance of eddy diffusion on molecular mixing is thus explicitly recognised. The equation is more often given in the form

$$z^m \frac{\partial\chi}{\partial x} = \alpha_2 \frac{\partial}{\partial z}\left(z^{1-m}\frac{\partial\chi}{\partial z}\right) \quad \text{.. (25)}$$

Where χ stands for the excess of a particular property acquired in moving a horizontal distance x, disregarding the original distribution of θ and its subsequent redistribution. It is soluble under practically any boundary conditions provided m is constant, and the theory has been tested in the laboratory for the turbulent transfer of momentum, heat and vapour above aerodynamically smooth surfaces (to which it strictly applies) with excellent results—see Pasquill[12] and others. It can only be applied to the atmosphere under conditions for which m is constant with time, that is, when the lapse rate of temperature is not varying or when the wind is strong. For the problem of the diurnal variation of various properties, m is a function of t, the time, not necessarily a simple one, and the mathematical difficulties of solution become prohibitive.

Sutton's formula leads to power laws for the profiles and diffusivities of the various properties in the steady state, and a linear law for the distribution of the mixing length with height. Frost[13], on the hypothesis that

$$l = z^{1-m} z_0^{\,m}, \quad \text{.. (26)}$$

where z_0 is a length characterizing the degree of roughness of the surface, arrived at an equation identical in form to Sutton's, but the resemblance between the two theories is only superficial. In the first place Sutton did not use equations (18) and (19) from which Frost started. Secondly, substituting this expression for the mixing length in equation (19), we easily get

$$\bar{u} = \frac{1}{m}\sqrt{\left(\frac{\tau_0}{\rho}\right)} \cdot \left(\frac{z}{z_0}\right)^m,$$

which is a power law, and if we accept von Kármán's principle of dynamical similarity, as Sutton did, the value for $\bar{u}$ when substituted in (20) gives $l = k_0 z/(m-1)$, which is inconsistent with (26). Frost dealt with the evaporation from a plane water surface and gave a very elegant mathematical solution of equation (25) for the relatively simple boundary conditions that obtain in this case. His results when applied to the average drift of air over

the Atlantic Ocean and later over the British Isles, were in remarkable agreement with observations. He assumed, among other things, that initially the distribution of moisture in the vertical was constant, and that there is no mean evaporation from a land surface. The former is unlikely and the latter is nothing like true except in winter (see Sumner[14]). Because of these limitations the paper cannot be regarded as rigorously confirming Sutton's theory under atmospheric conditions.

Sutton, himself, has recently produced a paper[15] describing experiments on the diffusion of gases and smokes in the atmosphere under conditions of small temperature gradients, carried out several years ago at the Chemical Defence Experimental Station, Porton. There were, however, considerable discrepancies between the unmodified theory and practice, all of which could be attributed to the fact that the earth's surface is not usually aerodynamically smooth. More recent (unpublished) work at Porton, under Mr. K. L. Calder, seems to indicate that atmospheric diffusion can be very satisfactorily predicted provided surface roughness is taken into account. Although the approach is different, the evaporation formulæ derived are identical with Sutton's in the particular case of a smooth surface, while those obtained for rough surfaces are in excellent agreement with observations on the diffusion of smoke and vapour in the lower atmosphere under adiabatic conditions. These results are very encouraging and, it is to be hoped that a complete account of them will soon be published.

Retrospect and prospect.—There have been several omissions in this essay without which a really comprehensive survey of the subject is impossible. Among them are the writings of Rossby and Montgomery in America, and the work of G. I. Taylor on diffusion by continuous movements in England. Taylor's theory is one of the most remarkable in the entire field; it is still growing and may, in the long run, throw light on many practical problems. Even a complete treatise on turbulence, however, would show significant gaps in our knowledge. Little is known, for example, about the correlation between the eddy velocities of the same fluid element at different times or between the various diffusible properties, or the origin of turbulence. Does turbulence start at the boundaries, and "diffuse" upwards, like vorticity in an incompressible viscous fluid, or can it appear spontaneously in the free atmosphere? The answer to this, and many other questions, lies in the future. The greatest difficulties arise in that part of the atmosphere immediately above the earth's surface; fortunately it is the easiest to explore, and in this connexion, much experimental work has been done, but much remains to be done. What strikes one most about the subject, is the amazing web of simplifying assumptions that has been spun, requiring a very nimble and highly mathematical spider safely to negotiate it. Several of its strands are wearing thin; most of them need a periodic redusting. Looking back it cannot be said that we have yet mastered the intricacies of fluid flow in a turbulent medium. The motion itself defies the imagination, and creation of the necessary working concepts defies the intellect. One may conjecture, however, that future progress, if it follows traditional lines, will be towards a greater complexity, in which it will be necessary to take account, in a suitable mathematical form, of the fluctuations of the transferable property in question, the eddy velocity (the mechanism) and possibly the atmospheric pressure as well (the driving agency). The

further development of micro-instruments to measure atmospheric fluctuations will undoubtedly be of primary importance in research.

But there is another alternative to the slow painstaking development of existing ideas and analysis of observational data, although it is one that is perhaps very remote. Taking a broader view, it is evident that the fundamental difficulties are common to science in general. The greatest obstacle seems to be the impossibility of forming an adequate concept of process. This partly arises because of an over-emphasis on the purely quantitative aspects of phenomena, which has been a necessary, and very profitable, preoccupation of scientists for centuries. Science, however, has never been able completely to disregard the qualitative, and it is widely felt nowadays that the old dualism of quantity and quality is breaking down. What will ultimately emerge it is impossible to say—one can seldom see far beyond the horizon—but it may be of radical importance to all branches of meteorology.

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A NOTE ON THE DEPRESSION OF JANUARY 9–10, 1948

BY E. J. PERCIVAL, B.A.

On January 9–10, 1948, a small depression moved on an approximately easterly track from south-west of Ireland in the early morning of the 9th to near Warsaw on the afternoon of the 10th. Certain features of the movement and the variations of intensity of this depression appeared worth investigating.

History of the depression.—Figs. 1–4 illustrate the movement of the depression and the changes in its central pressure. At 0300 G.M.T. on the 9th the centre was south-west of Ireland at about 51°N. 13°W. In the next

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Photograph by R.A.F.

CUMULONIMBUS CLOUD AT OLDENBURG, 1745, JULY 27, 1944

Base of the cumulonimbus at 4,000 ft., top at 31,000 ft. Top of stratocumulus layer at 9,000 ft.

FIG. 3—LOOKING NORTH FROM THE CONTROL TOWER

FIG. 4—LOOKING SOUTH TOWARDS THE ENCLOSURE

FLOODS AT BALLYKELLY, NORTHERN IRELAND

These photographs were taken on July 30, 1947, two days after the flooding, when it had subsided a little.

six hours it moved a little south of east* to about $50\frac{1}{2}$°N. 9°W. at 0900, and then on a more north-easterly track to $51\frac{1}{2}$°N. 5°W. at 1500 and 53°N. 1°W. at 2100. It then turned to the right and accelerated, reaching $52\frac{1}{2}$°N. $4\frac{1}{2}$°E. by 0300 on the 10th (giving heavy gales in Holland and the Rhineland), and then moved quickly eastward to $52\frac{1}{2}$°N. 10°E. at 0900 and 53°N. $17\frac{1}{2}$°E. at 1500.

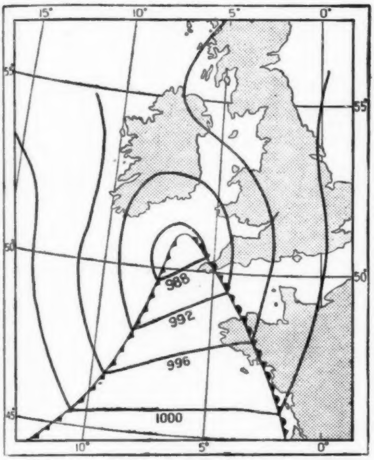

FIG. 1—1200 G.M.T., JAN. 9, 1948

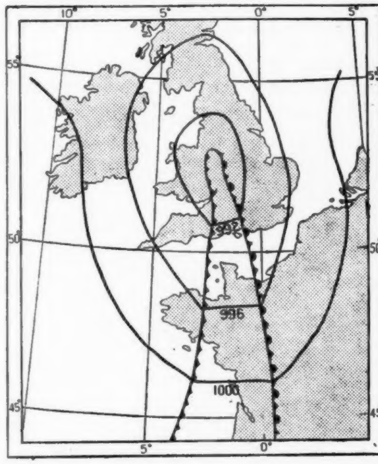

FIG. 2—1800 G.M.T., JAN. 9, 1948

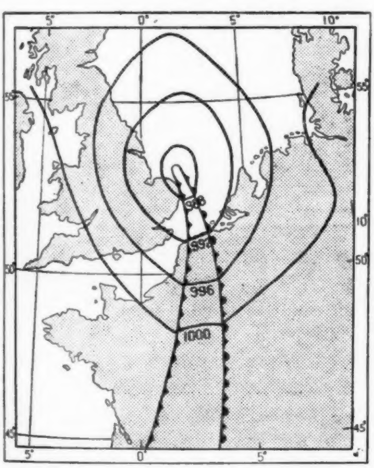

FIG. 3—0000 G.M.T., JAN. 10, 1948

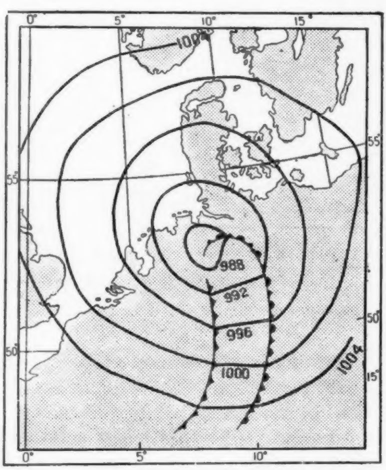

FIG. 4—0600 G.M.T., JAN. 10, 1948

The depth showed little change at 986 mb. for the first six hours, and then filled a little to 988 or 989 mb. at 2100. During the next six hours there was a rapid deepening, to 984 mb. at 0300 on the 10th, followed by a steady filling up to 991 mb. at 1500. At 0300 on the 9th, the depression appears on the

*This is doubtful, as the position of the centre at 0300 is somewhat doubtful, and may have been a little further to the south.

chart as a secondary at the tip of a narrow warm sector, but during the next few hours this sector occluded rapidly, so that, by 0900, the depression had only a very weak "false" warm sector between the two parts of the occlusion. Later the backbent occlusion developed cold-front characteristics, and it may have been that the introduction of a new supply of cold air from the north led to some regeneration of the depression. However, the frontal analysis seems to give a very inadequate picture of what happened. An analysis is attempted of regarding the depression as essentially a non-frontal closed circulation below wave-shaped upper isobars, with the horizontal convergence or divergence aloft in the neighbourhood of the centre as the important factor.

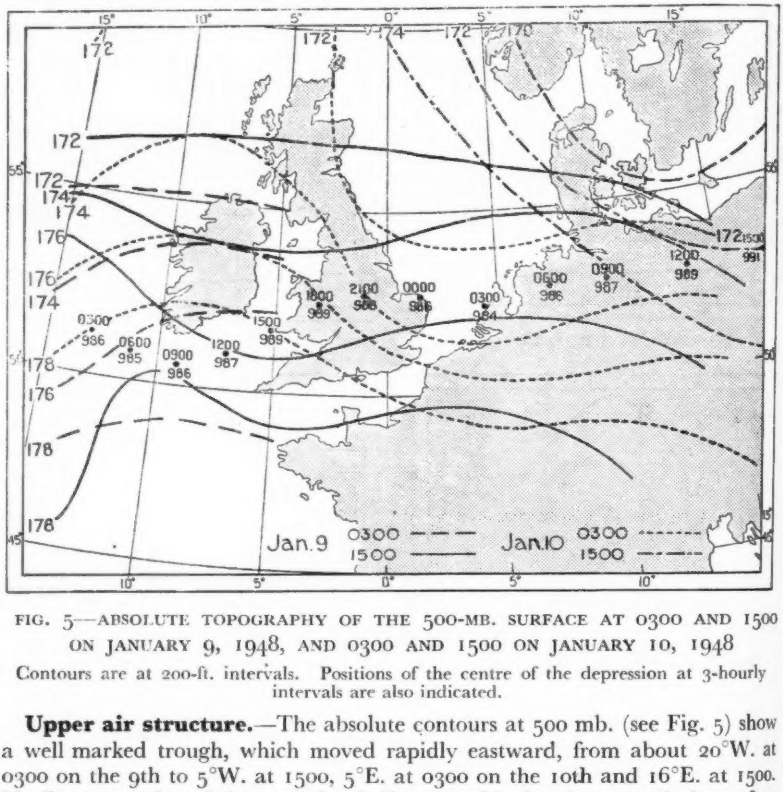

FIG. 5—ABSOLUTE TOPOGRAPHY OF THE 500-MB. SURFACE AT 0300 AND 1500 ON JANUARY 9, 1948, AND 0300 AND 1500 ON JANUARY 10, 1948

Contours are at 200-ft. intervals. Positions of the centre of the depression at 3-hourly intervals are also indicated.

Upper air structure.—The absolute contours at 500 mb. (see Fig. 5) show a well marked trough, which moved rapidly eastward, from about 20°W. at 0300 on the 9th to 5°W. at 1500, 5°E. at 0300 on the 10th and 16°E. at 1500. Until 1500 on the 9th it was quite shallow; at this time it overtook the surface depression and became rapidly deeper. The height of the 500-mb. surface at the centre of the depression fell from about 17,500 ft. at 0300 and 1500 on the 9th to 17,300 ft. at 0300 and 17,200 ft. at 1500 on the 10th. The corresponding thicknesses (Fig. 6) of the 1000–500 mb. layer were 17,800 ft., 17,800 ft., 17,600 ft. and 17,250 ft. respectively. Thus, during the latter part of its history while the surface depression was moving approximately with the upper trough, the air in its neighbourhood in the lower half of the atmosphere got steadily colder.

Movement of the upper trough.—Certain features of the movement of long waves in the atmosphere have been discussed by J. Bjerknes and J. Holmboe*. The quantitative results theoretically derived by these authors are not properly applicable in the present case, as the departure is too great from the idealised wave form they consider; in particular, their fundamental assumption is violated, that the whole wave from wedge to wedge is situated symmetrically with respect to the trough. However, from a qualitative viewpoint their results are of interest.

Horizontal mass divergence and convergence in the long waves.—In the case of geostrophic flow along parallel straight isobars at any level

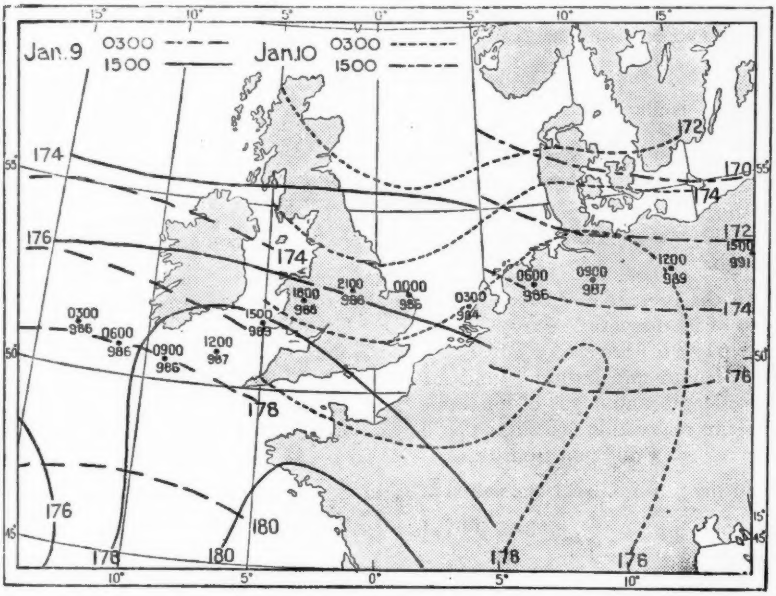

FIG. 6—RELATIVE TOPOGRAPHY OF THE LAYER 1000–500 MB. AT 0300 AND 1500 ON JANUARY 9, 1948, AND AT 0300 AND 1500 ON JANUARY 10, 1948

Thickness contours are at 200-ft. intervals. Positions of the centre of the depression at 3-hourly intervals are also indicated.

(or contours on an isobaric surface), or of "gradient flow" round parallel curved isobars, the stream lines will run parallel with the isobars, and will give constant transport capacity of air between the isobars, and there will be no horizontal mass convergence or divergence. In general, however, such conditions do not apply exactly, often not even approximately, and convergence or divergence may arise in two different ways:—

(*a*) If the stream lines are not parallel to the isobars, there will generally be a difference between the mass of air entering the area between two isobars in any region and that flowing out across the isobars, giving rise to *transversal* mass divergence (or convergence).

*BJERKNES, J. and HOLMBOE, J.; On the theory of cyclones. *J. Met., Milton, Mass.*, **1**, 1944, p. 1.

(b) If the transport capacity between two isobars varies along their length, there will similarly be a difference between the masses of air entering and leaving the region between the isobars, giving rise to a *longitudinal* component.

In the case of wave-shaped isobars (or contours) both these components are of importance.

Transversal mass divergence.—For the tranversal divergence Bjerknes and Holmboe derive the rule that " The transversal divergence and the relative zonal wind ($\bar{v}-c$) have the same sign in the region to the east of the trough and opposite signs in the region to the west of the trough."

Longitudinal mass divergence.—Bjerknes and Holmboe derive for the speed c of a symmetrical wave with no longitudinal divergence a formula of the form

$$\bar{v} - c = v_c$$

where $\bar{v}$ is the mean zonal wind, i.e. the mean of the westerly components through the trough and wedge; and v_c is a critical speed depending mainly on geometrical considerations—the wave-length, the shape of the wave, and the latitude. If $\bar{v} - c > v_c$ there will be a bottleneck at the trough, and convergence to the west of the trough, with divergence to the east; and correspondingly if $\bar{v} - c < v_c$ the bottleneck is at the ridge, with convergence to the east of the trough.

In the present case v_c cannot readily be evaluated theoretically, but some idea of its magnitude may be obtained. For the simpler case of a sinusoidal flow pattern (discussed by Bjerknes and Holmboe) v_c is a function only of the wave-length and latitude; and for the present case (in latitude 50°N., with wave-length about 36° of longitude, and decreasing), v_c is less than 6 m.p.h. It seems reasonable to assume that for our actual case the order of magnitude of v_c is not very different from this.

At the 500-mb. level, the values of $\bar{v}$ and of c were approximately as follows:—

	0300, 9th		1500, 9th		0300, 10th		1500, 10th
$\bar{v}$ (m.p.h.)	40		45		50		55
c (m.p.h.)		50		35		40	

(The value of c during the first interval must be regarded as suspect, because of the inadequacy of data over the Atlantic, and consequent doubt as to the position of the trough at 0300 on the 9th.)

Thus the value of $\bar{v} - c$ was probably negative, and so subcritical, until 1500 on the 9th, and thereafter fairly constant at about 12 m.p.h., and almost certainly supercritical.

Two other points have to be noted:—

(a) In the normal case, where the temperature falls from south to north, $\bar{v}$ increases with height, and where the speed of the trough is the same at all heights (as was approximately the case from 1500 on the 9th), we can expect $\bar{v} - c$ to be subcritical at low levels, but supercritical at high levels. The height of the level of non-divergence, where $\bar{v} - c = v_c$, will determine whether the low-level bottleneck at the ridge or the high-level bottleneck at the trough is the more important.

(*b*) In the low-level closed-isobar régime convergence is normal, other factors being small in comparison with surface friction.

Period: 0300 to 1500 on January 9.—During this first phase the depression followed a " normal " course for an occluding secondary, filling slowly, and turning towards the left. This, however, appears to be somewhat fortuitous. Normally, this course of an old depression is associated with the closed circulation reaching to a considerable height (with corresponding preponderance of convergence over any high-level divergence causing rising surface pressure) and cold air being pulled round to the west and south of the depression (causing the upper flow and the track of the centre to back). In the present case, the shallowness of the upper trough and its distance from the surface centre indicate that the closed isobar system extended to no great depth, and another reason for the filling up and the curvature of the track must be looked for.

During this period, the value of $\bar{v} - c$ is doubtful, as indicated earlier, but was probably negative and almost certainly subcritical. In the region of the surface centre, to the east of the upper trough, there would be some convergence in the lower closed circulation and further convergence or, at least, little or no divergence over the upper atmosphere as a whole. With $\bar{v} - c$ negative, there would be transversal convergence at 500 mb. and, provided $\bar{v} - c$ is merely subcritical, there will be longitudinal convergence at this and all lower levels. Consequently rising pressure is to be expected at the surface.

Following the rough rule that the track of the depression is in the general direction of the upper flow, we should expect it to move somewhat north of east. At 0300 the gradient wind, at 500 mb., above the surface centre was about 240° 50 m.p.h., while measured winds were:—

	700 mb.		500 mb.	
	°true	m.p.h.	°true	m.p.h.
Larkhill	250	21	280	52
Valentia	210	25	240	30

The speed of the depression was 30 to 35 m.p.h.

It may be noted that the depression was centred to the east of the upper trough and therefore in a region of south-westerly upper winds. The 500-mb. wind at Larkhill belongs to the region ahead of the next ridge eastward; the winds at Valentia are too light to be typical, as Valentia was somewhat north of the surface centre.

Period: 1500, January 9 to 0300, January 10.—During this period, the fast-moving upper trough having overtaken the surface depression, their interaction becomes the important feature.

The surface depression pulls down colder air from the north on its west side, so tending to develop an upper air trough in this region, which leads, in effect, to a slowing up and deepening of the upper trough.

The reduction of the speed c of the trough means that $\bar{v} - c$ becomes supercritical through the major part of the upper air mass, with consequent preponderance of convergence (and so rising surface pressure) to the west of the trough and of divergence (and falling surface pressure) to the east of the trough.

The longitudinal and transversal components of divergence have the same sign, and augment one another, negative to the west and positive to the east of the trough. The surface-pressure changes indicate an acceleration eastwards of the surface centre into the area east of the upper trough, where the preponderating divergence leads to further deepening. The fact that the track was somewhat south of east might be due to the stronger winds on the south side of the low, leading to the divergence ahead of the trough being more marked towards the south than further north.

Period: 0300 to 1500, January 10.—In this period we are approaching something more like the normal filling-up stage of a depression. The deepening of the upper trough as colder air is drawn in behind the surface low is associated with increasing vertical extent of the surface closed-isobar system; and the convergence in this system outweighs divergence ahead of the trough at greater heights. The rapid eastward movement is still associated with the rapid movement of the upper trough.

Later history of the depression.—During the 24 hours following the period already discussed, the depression continued its rapid eastward movement (at about 40 m.p.h.) to near 55°N. 40°E. at 1500 on January 11. By this time closed isobars extended up to 500 mb., with the axis of the vortex inclined from the vertical towards the north-west. Little further filling had occurred, the pressure at the surface centre being 993 mb. Longitudinal and transversal divergence ahead of the upper trough may account for the failure of the surface low to fill further, and also for the fact that during this last phase it tended to move a little more ahead of the upper trough.

As remarked in an earlier paragraph, a low which extends through a considerable height as a closed circulation will usually tend to turn north-east. However, in the present case the low moved into steadily colder air, and this could account for the continued eastward track.

Conclusion.—This depression caused heavy gales in the early morning of January 10, winds of Beaufort force 8 or 9 being reported over Holland between midnight and 0300, and in the Rhineland between 0300 and 0600. By 0900, gales had already almost completely ceased. These gales were only forecast very late, and their rapid disappearance was also unexpected; it was this that drew particular attention to the apparently eccentric history of the depression, and caused the present note to be prepared. It is of interest that the Central Forecast Office (C.F.O.) bulletin issued about 1630 G.M.T. on the 9th forecast for 1200 on the 10th a position for the centre at 55°N. 2½°E., about 500 miles from its actual position, with a depth of 990 mb.; while as late as the 2230 G.M.T. bulletin the position forecast for 1800 on the 10th was 55°N. 13°E., with a depth of 993 mb., against an actual position of 53½°N. 20°E.

While the present investigation appears to give a reasonable explanation of the development of the depression from the forecaster's viewpoint two major difficulties stand out:—

(*a*) Nothing much could have been attempted in the way of analysis until the contours at 1500 G.M.T. on the 9th were available, which even for the restricted area under consideration would have been late in the evening (the C.F.O. bulletin arrives about midnight).

(b) I see no real hope of *timing* the changing phases of the depression's history, of deciding just when, for example, the acceleration and deepening of the second phase would occur or, for that matter, what its extent would be and how long it would last.

At the same time, it is hoped that the investigation may prove of interest, both, in that it provides a rational explanation of synoptic developments over which both the principal British forecast offices in the area went astray, and that it may draw attention to an analytical method which could prove useful on other occasions. It may also provide a warning as to the type of development that can occur where a small depression of little vertical extent is situated below an upper atmosphere with high winds, and especially one with wave-shaped contours moving independently of the surface depression.

METEOROLOGICAL RESEARCH COMMITTEE

The 48th meeting of the Meteorological Research Committee was held at the Meteorological Office, Harrow, on Thursday, May 8, 1947.

The papers considered included a review of progress in the development of meteorological instruments, two papers on the accuracy of radar methods of wind measurement, a note on balloon soundings up to a height of 30 Km., and a paper on the prediction of evaporation from saturated surfaces.

ROYAL METEOROLOGICAL SOCIETY

At the meeting of the Society held at 49 Cromwell Road, on April 19, 1948, the Symons Memorial Lecture was delivered by Dr. H. G. Booker on the subject " Some problems of radio meteorology ".

Dr. Booker, one of the leading workers during the war on the propagation of high-frequency electromagnetic waves through the atmosphere, began his lecture by stating that the problems he would deal with were those found in the refraction of short radio waves of length less than 10 m. in the lower layers of the atmosphere. When there was a steep gradient of temperature or humidity these short waves were refracted with exceedingly important effects.

To demonstrate the effects of refraction slides were projected showing the areas, around Malta, visible on a radar screen on the island on days of normal propagation with little refraction and those visible on a day when the refraction was such as to produce abnormally long-range radar vision. Dr. Booker pointed out, from these slides, that abnormally long-range vision was more of a nuisance than a help since it made the reflections, it was desired to see, of high-flying aircraft invisible against a background of unwanted ground echo and could show confusing echoes of points, beyond the range for which the apparatus was calibrated, appearing as " second-sweep " echoes at half their proper distance. Other slides showed echoes from up to 200 miles, obtained at night by radar near Calcutta when a radiation inversion produced abnormal refraction compared, with those from only 30 miles by day when refraction was small. The most striking effects, however, were revealed in a slide showing, during the hot season, echoes obtained by radar at Bombay from the Arabian coast over 1,000 miles away, the same radar having a range of only 15 miles under normal conditions.

These abnormal effects occurred, Dr. Booker pointed out, when the high-frequency waves, which normally travelled in straight lines, were bent down towards the surface of the earth. In a dry atmosphere an increase of temperature with height at the rate of 6°F./100 ft. imposed a degree of downward bending on the rays equal to the curvature of the earth. A decrease of humidity mixing ratio with height of ½ gm./Kg./100 ft. would have the same result. Often the two effects of temperature and humidity acted together so producing an even greater degree of bending. If the conditions favourable for downward bending occurred only in a narrow belt near the surface of the earth, then high-frequency waves would be trapped within the belt which thereby formed a species of radio duct guiding the waves. The energy of waves of long wave-length, on the other hand, would leak out of the top of the duct. Long waves, in fact, are affected only by the meteorological conditions over a great depth of the atmosphere. For waves of 1-m. wave-length the suitable conditions must extend up to 500 ft. to be effective in trapping the energy, but for waves of 10 cm. they need extend up to only 100 ft.

The height of the layer containing the conditions favourable for downward bending was as important as its depth since a high layer could only refract the waves downwards when they met it at a glancing incidence and the higher the layer the greater the angle of incidence of the rays from a transmitter on the ground. Such layers at heights of over 5,000 ft. were of little importance in radio propagation.

Dr. Booker then turned to the meteorological circumstances in which steep inversions of temperature and/or steep lapses of humidity could occur. There were three types, (*a*) nocturnal radiation overland, (*b*) movement of air from land to sea, and (*c*) subsidence. In the case of nocturnal inversions the humidity often tended to increase with height so partly or wholly nullifying the effect of the inversion while in the case of subsidence the inversion was often too high. Movement of warm dry air from land to sea gave the most spectacular effects, such as those found over the Arabian Sea in the hot season. It was also of great practical importance since many radar stations were necessarily located on the coast looking out over the sea.

The radio worker, Dr. Booker pointed out, needs very precise information on the vertical gradients of temperature and humidity for calculating the effective range of his transmitters. In special experiments detailed measurements of these gradients can be made but they cannot be made everywhere it is proposed to establish new transmitters. Dr. Booker emphasised that a general theory from which the temperature and humidity gradients can be deduced from the ordinary meteorological surface observations of temperature, humidity and wind is urgently needed. This was essentially, in his view, a problem in eddy diffusion. During the war efforts had been made to solve the diffusion equation but with only moderate success. After the assumption of constant coefficient of turbulence had been tried and found of no value, he had worked with the conjugate power laws of O. G. Sutton in which the horizontal velocity is taken as varying as z^m (z = height, $0 < m < 1$), and the coefficient of turbulence as z^{1-m}. The differential equation for diffusion in air flowing from a warm land to a cool sea could be solved with this assumption, but there was a serious difficulty in lack of information about the value of the index m, except that it was likely to be about zero in unstable conditions and unity in

Reproduced by courtesy of Capt. A. W. Ford

THE SHIP'S CREW OF O.W.S. *Weather Recorder*

O.W.S. *Weather Observer*
Taken from the *Weather Recorder.*

very stable conditions. Comparisons of observed profiles of potential temperature and humidity in air flowing from land to sea were made with calculated profiles and the best values of *m* deduced. It was found that the values of *m* obtained from the profiles of potential temperature were closely correlated (correlation coefficient : 0·9) with those found from the humidity profiles. A less satisfactory result was that the expected connexion between the value of *m* and the difference between the potential temperature at the ground and at a height could not be found. What was found was that the value of *m* increased with the height to which the diffusion had reached. The conjugate power law was, thus, not very satisfactory.

On solving the differential equation it was found that the gradients of temperature and humidity were very sensitive to the variation of the coefficient of turbulence with height but insensitive to the variation of wind. An attack on the coefficient of turbulence was therefore the next step. General considerations showed that the coefficient should increase with height in the lowest layers, reach a maximum at some hundreds of feet, and then decrease again. Such a kind of variation with height explained the dependence of the value of *m* in the power-law theory on the height which diffusion had reached.

Finally, Dr. Booker pointed out that the differential equation for the variation of potential temperature and humidity with height in a subsidence inversion was simpler than the corresponding equations for radiation and advection inversions and suggested that, on that account, subidence inversions should be investigated before the nocturnal and radiation ones.

NOTES AND NEWS

Ocean weather ships

Opposite is a photograph of the *Weather Observer* taken from the *Weather Recorder*, and facing p. 136 is a photograph of the crew of the *Weather Recorder* which was concerned in the rescue of the crew of a Norwegian ship off the west coast of Scotland. An account of the rescue, given by Captain A. W. Ford of the *Weather Recorder*, is given below.

Rescue of Crew of S.S. " Veni "

Upon completion of fuelling the O.W.S. *Weather Recorder* sailed from the Tail of the Bank at 1608 G.M.T. on January 10 for Station " I ". The wind was increasing in force until, by midnight, a SE. whole gale was blowing with a heavy south-easterly sea. Ship was rolling and pitching heavily.

Off Rathlin Island at 0012 on the 11th, an S.O.S. was intercepted from the Norwegian steamer *Veni*: " Position Torran Rocks west of Colonsay sinking must try leave." This was received at 0047. Course was set for the Torran Rocks and speed increased to 150 revolutions. The following signal was sent to the *Veni* via Malin Head who was controlling the distress: "Am proceeding to your assistance with the utmost dispatch. Will be with you at 0500." Further signals and D.F. bearings were received which placed the ship on the west side of Colonsay. The radar was checked and rechecked all the way to the distress and it was found that it was working well, provided that the aerial was lined with the P.P.I. mask each time we altered course. I didn't feel completely happy about the location of the wreck; so the searchlight

was flashed into the air when the north end of Islay was reached and the *Veni* responded with red rocket flares. Course was altered into the shore a couple of miles away.

While all this was going on the lifeboat was prepared, the engine tried every half-hour, scramble and floater nets prepared, also the rubber dinghys, whilst the sick bay was prepared for any casualties. The night was pitch black and the gale worse than ever; to make matters worse terrific heavy rain kept on blotting out our only navigational light, that of Dubh Artach. Full use was made of the radar and the echo-sounding machine, and we closed the wreck to inside a mile. Many signals had been passed between the ships, the Master of the *Veni* giving me all the latest news of the position. As it was only a couple of hours to daylight the Master of the *Veni* signalled he would wait until daylight. The *Weather Recorder* stood off to westward at a mile to a mile and a half distant. I requested the Master to inform me if he required me to use my boat, but it could be seen that the *Veni* had her boats in the water by the lanterns in them.

Red flares were sighted so I thought there must be something doing; I closed the wreck again and the flares were obviously from the boats. The boats steered to northward under oars and I came around, close to the wreck, stemming the wind. The sea had dropped and no difficulty was experienced in getting the survivors on board, who were fed and bedded down. Only one injured man was taken to the sick bay. His wounds were washed and dressed; he appeared quite comfortable.

At 0700 we informed Malin Head who cleared the distress; the Port Patrick lifeboat was informed that his services would not be required. Course was set for Greenock and speed at 160 revolutions. The weather had moderated considerably, Greenock was reached at 1800 on the 11th. All the officials met the ship and the survivors were taken to the Clydesdale Sailors' Home.

Without the radar it would have been impossible to close the wreck. It was very tiresome having to line up the aerial each time we altered course, but it was achieved. The crews were very keen and nearly all wanted to man the lifeboat.

A. W. FORD
Master, Ocean Weather Service

O.W.S. "Weather Recorder", Greenock, January 14, 1948.

Severe local thunderstorm, Lough Foyle area

Thanks are due to Mr. J. Porter of the rainfall station Moneydig, Garvagh, Co. Londonderry, for calling attention to what he describes as "one of the worst local thunderstorms" which "swept parts of Co. Londonderry and Tyrone during the morning of July 28, 1947."

Press accounts and rainfall records confirm that the storm of approximately 3-hr. duration, was confined to a comparatively small area of Northern Ireland and was contained within the mountains surrounding Lough Foyle, of which the Sperrins form the main boundary to the east and south.

The three rain-gauges in the coastal plain at the foot of the hills in the storm area, i.e. Ballykelly, Castle Rock and Dungiven, recorded 2·37 in. (60·2 mm.) 2·14 in. (54·4 mm.), and 1·12 in. (28·5 mm.) respectively during the period

of the storm. It is very probable that even greater amounts of rain fell in the hilly districts in the vicinity, but outside this local area, little or no rain was recorded by the many rain-gauges in Northern Ireland.

The beds of small streams which normally flow from the surrounding hills to Lough Foyle, were unable to contain the sudden increase in the volume of water and severe flooding occurred in many places. The onrush of water caused very considerable damage which was described by the local press as "the most severe visitation in living memory."

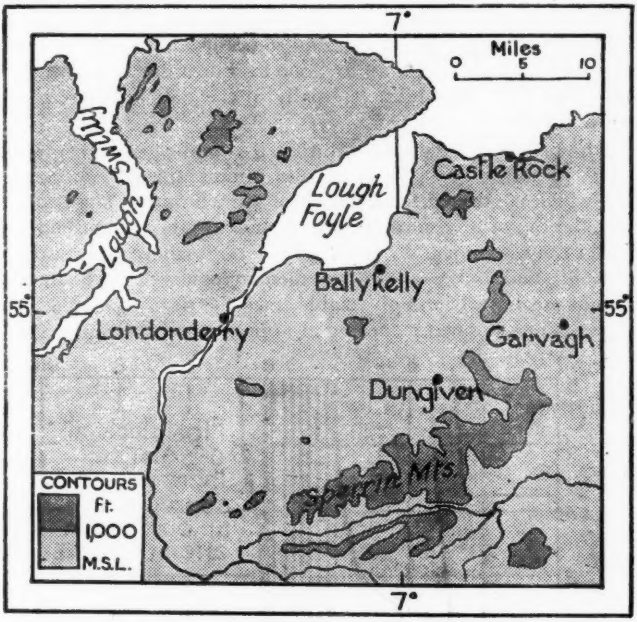

FIG. 1—MAP OF THE AREA ROUND BALLYKELLY

A published report by the County Surveyor of the districts concerned, given to a Rural Council on October 6, 1947, after the most thorough investigation lasting two months, stated that "the thunderstorm of July 28 caused devastation unparalleled in the records of the district. Deluges of flood water, which followed torrential rain and cloudbursts, washed away miles of road and their foundations. Many others were made impassable by hundreds of tons of debris. Many large bridges and culverts were damaged or completely washed away. Some roads were so badly damaged that a considerable mileage would require complete reconstruction."

The following account of the storm is taken from a report from H.Q., R.A.F.N.I., Aldergrove:—

"A thunderstorm with heavy rain resulted in flooding of the airfield at Ballykelly on the morning of July 28, 1947. The rainfall during a 3-hr. period (5.15 a.m. D.B.S.T. to 8.15 a.m. approximately) amounted to 2·37 in. (60·2 mm.). The heaviest fall occurred between 7 a.m. and 8 a.m., when

the recorded rainfall was 1·68 in. (42·6 mm.). This constitutes a 'remarkable' fall. Within two hours of the cessation of the heavy rainfall, flood water from a near-by river which had burst its banks, spread over the airfield to a depth of 2 ft. in places. The pressure distribution at the time was fairly uniform generally over the British Isles, with very shallow lows forming over Ireland. A weak front had moved slowly south on the previous day, become stationary across mid Ireland, and later dissipated. Surface winds were light variable or easterly, and between S. and SW. 20–30 kt. above 10,000 ft. over Northern Ireland. Maximum surface temperatures on the 27th were mainly of the order 62° to 66°F. over most of Ireland, but reached 74° to 75°F. locally in central and west-central Ireland, causing some instability in the lowest layer. Previously, air was fairly stable up to 3,000 ft., but unstable above that height. The uplift of air over high hills, especially in the Ballykelly area, might well have been a contributory cause."

No rain had fallen at Ballykelly during the 24-hr. period preceding the storm. The rainfall trace (Fig. 2) shows almost abrupt commencement of heavy rain which continued for a period of 3 hr. 6 min. The trace also ends abruptly at the top of its recording, but in this case the abrupt end was due to immersion of the instrument by flood water. A further unmeasured quantity of rain obviously fell, but a note by the meteorological observer states that this amount could not have been appreciable since the storm ceased a few minutes after the rain-gauge stopped recording at approximately 0615 G.M.T.

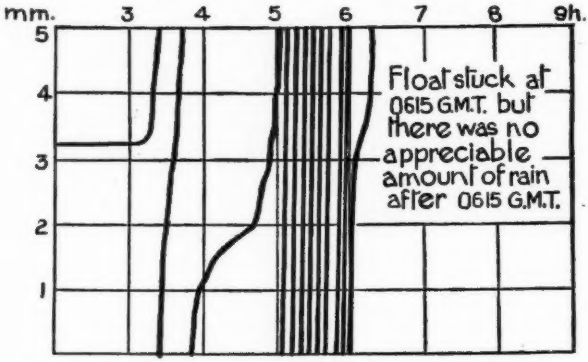

FIG. 2—COPY OF THE RAINFALL TRACE AT BALLYKELLY, JULY 27, 1947

Photographs (facing p. 129) were taken at the R.A.F. station, Ballykelly, two days after the airfield became flooded. Fig. 3 was taken from the Control Tower. The Lancaster aircraft shown in the photograph had previously been marooned and had just taken off, having used one runway which, for the first time in three days, had become partly clear of water. Fig. 4 was also taken on July 30 after the floods had subsided somewhat. It will be seen that the meteorological instruments enclosure, which was covered to a depth of 2 ft. on the morning of July 28, was still surrounded by water.

At Garvagh, which is on the north-eastern side of the Sperrin Mountains, only ·03 in. (0·76 mm.), were recorded during the storm.

A. WALTERS

WEATHER OF APRIL 1948

From the 1st to the 8th deep depressions, with associated troughs, passed across or near to the British Isles. From the 9th to the 16th pressure was relatively high, after which there followed a week with irregular shallow depressions. From the 24th to the 27th there was a second period with high barometer, but after the 27th the anticyclone moved away to the south-west and an irregular system of depressions spread in from the north-west.

The mean-pressure map for the month shows a large high-pressure area extending from Portugal westwards to the American coast, with pressure about 1025 mb. near the Azores, and an area with pressure below 1010 mb. extending eastwards from southern Greenland to Finland and southwards to include most of Scotland and Norway. Pressure was below the average over most of north-west Europe, and in Greenland, Iceland and Spitsbergen; it was above the average over a large area centred north-west of the Azores and including the eastern parts of North America south of Labrador.

The weather over the British Isles was generally warm and sunny, with rainfall not very different from the average on the whole. Unsettled weather prevailed until the 9th, when a ridge of high pressure moved in over the country. Subsequently conditions were mainly anticyclonic until the 16th, apart from occasional slight rain in the north and west. A spell of warm, thundery weather ensued, which was followed by another spell of fair sunny conditions. The closing days were cool and rather unsettled with shallow depressions moving south-east across the country. The range of pressure was exceptionally great for April; at 0300 on the 1st pressure fell to 953 mb. in the Hebrides and on the 26th it reached 1043 mb. in Ireland. Mean temperature again appreciably exceeded the average, the excess being roughly between 2° and 3°F. In England and Wales this was the thirteenth successive month for which the mean temperature exceeded the average for the period 1906–35. So long a series of consecutive warm months has not occurred since comparable values were available, that is, since 1901. The first six days and the last three were relatively cold, while the warmest week was that ending on the 24th.

Rainfall exceeded the average over most of Scotland except in the east and in the south-west coastal districts. In England and Wales more than the average occurred in an area extending from Essex across the southern Midlands to mid Wales, in an area in the extreme north, over parts of the south-west and in small scattered areas elsewhere. In Northern Ireland more than the average occurred at Londonderry and Armagh and less than the average elsewhere. The duration of bright sunshine was substantially in excess of the average except locally in the west and north of Scotland; at Croydon it was the sunniest April since records started in 1922 and at Hampstead the sunniest since 1914.

The general character of the weather is shown by the following table:—

	Air Temperature			Rainfall		Sunshine	
	Highest	Lowest	Difference from average daily mean	Percentage of average	No. of days difference from average	Percentage of average	Percentage of possible duration
	°F.	°F.	°F.	%		%	%
England and Wales ..	74	19	+2·5	96	−1	127	46
Scotland	68	19	+2·3	115	+1	107	36
Northern Ireland ..	67	30	+2·9	90	−1	112	40

CLIMATOLOGICAL TABLE FOR THE BRITISH COMMONWEALTH, DECEMBER 1947

Stations	Pressure		Temperatures								Relative humidity	Mean cloud amount	Precipitation			Bright Sunshine	
	Mean of day M.S.L.	Diff. from normal	Absolute Max.	Absolute Min.	Mean values Max.	Mean values Min.	Mean values ½ Max. and 2 Min.	Mean values Diff. from normal	Mean values Wet bulb				Total	Diff. from normal	Days	Daily mean	Percentage of possible
	mb.	mb.	°F.	°F.	°F.	°F.	°F.	°F.	°F.	%	tenths	in.	in.		hr.	%
London, Kew Observatory	1015·9	+3·3	55	23	46·0	38·3	42·1	+0·6	40·4	86	7·8	2·14	−0·15	14	0·7	8
Gibraltar	1020·5	+0·2	70	44	63·3	50·6	56·9	+0·9	52·0	82	3·6	3·22	—	8	—	—
Malta	1013·3	−2·9	71	42	60·5	51·7	56·1	−1·8	53·4	72	6·4	3·13	—	20	5·5	56
St. Helena	1014·9	—	70	55	67·1	57·0	62·1	+1·2	57·2	95	9·4	0·88	−0·45	11	—	—
Freetown, Sierra Leone	1010·5	+1·1	88	70	83·5	74·7	79·1	−0·8	73·9	81	5·4	2·53	+1·11	10	6·7	58
Lagos, Nigeria	1010·3	−0·2	92	66	88·5	70·8	79·7	−2·1	76·5	89	8·1	1·62	—	5	5·5	47
Kaduna, Nigeria	1009·9	—	94	53	90·2	57·9	74·1	−0·2	58·1	27	2·9	0·00	0·00	0	9·6	84
Chileka, Nyasaland	1012·5	−0·2	91	64	82·8	67·7	75·3	−0·8	69·5	75	7·3	4·87	−0·85	17	5·9	45
Salisbury, Rhodesia	1010·9	−0·5	82	57	78·5	60·5	69·5	+0·1	62·5	71	6·7	5·31	−1·79	17	6·4	49
Cape Town	1014·7	+0·4	95	54	77·8	60·6	69·2	+1·3	60·8	63	3·7	0·51	−0·30	4	—	—
Germiston, South Africa	1011·6	—	83	48	76·3	56·7	66·5	—	58·6	70	5·6	5·16	—	15	7·7	57
Mauritius	1013·9	+0·2	90	68	85·5	71·2	78·3	0·0	72·3	76	4·7	3·23	−1·45	16	10·1	76
Calcutta, Alipore Obsy.	1014·7	−0·9	86	51	79·4	58·6	69·0	+2·5	59·5	82	3·5	1·05	+0·81	6	6·7	62
Bombay	1012·2	−1·3	92	65	88·3	69·7	79·0	+1·6	66·9	72	0·8	0·00	−0·05	0	9·7	89
Madras	1012·2	−1·3	86	64	83·3	69·1	76·2	−0·5	70·3	87	5·7	0·57	−4·78	5	7·5	66
Colombo, Ceylon	1010·7	+0·4	87	67	84·8	71·9	78·3	−1·2	71·5	86	5·9	5·31	+0·19	8	7·0	60
Singapore	1009·7	0·0	88	70	84·8	72·7	78·7	−1·2	76·3	85	—	17·93	+7·37	21	—	—
Hongkong	1019·8	+0·1	83	42	70·0	57·6	63·8	+0·8	58·1	73	—	0·35	−0·68	11	5·6	52
Sydney, N.S.W.	1010·9	−1·0	94	58	76·3	63·7	70·0	−0·1	64·8	70	6·5	8·44	+5·58	21	6·4	45
Melbourne	1010·1	−2·6	98	50	74·7	55·1	64·9	+0·1	57·8	59	7·1	3·91	+1·64	14	6·2	42
Adelaide	1011·4	−1·9	99	49	78·7	58·1	68·4	−2·7	58·6	49	5·7	1·78	+0·75	11	8·2	57
Perth, W. Australia	1013·7	+0·5	100	53	77·5	57·6	67·5	−3·3	60·5	55	4·0	0·35	−0·21	5	10·9	76
Coolgardie	1011·8	+0·6	105	47	90·3	58·9	74·6	−1·1	58·8	43	2·7	0·00	−0·69	0	—	—
Brisbane	1011·8	−0·2	93	62	82·6	67·0	74·8	−1·6	68·5	71	6·2	8·14	+3·25	18	8·1	59
Hobart, Tasmania	1009·6	−0·1	83	42	68·7	51·7	60·2	0·0	54·5	63	8·0	4·91	+2·92	16	7·0	46
Wellington, N.Z.	1016·8	+4·6	—	43	67·6	53·4	60·5	+1·5	57·3	74	7·9	1·62	−1·60	11	7·0	46
Suva, Fiji	1007·3	−1·3	88	70	85·8	73·1	79·5	+0·5	75·5	85	6·9	5·88	−6·64	19	6·6	50
Apia, Samoa	1007·8	−0·5	88	72	85·8	74·6	80·2	+0·9	77·5	78	8·2	18·44	+4·55	22	5·5	43
Kingston, Jamaica	1013·6	−0·4	91	66	87·1	70·2	78·7	+1·0	71·7	70	3·7	1·56	−0·03	5	7·7	69
Grenada, W. Indies	1011·4	−0·4	87	65	85·0	75·1	80·1	+1·9	75·8	79	5·5	2·70	−4·50	23	—	—
Toronto	1018·5	+0·9	47	7	32·8	21·1	26·9	−0·2	24·3	—	7·0	2·39	−0·08	15	2·8	31
Winnipeg	1019·4	+0·7	33	−29	13·4	−4·2	4·6	−1·2	2·6	—	6·1	1·85	+0·91	14	2·4	29
St. John, N.B.	1010·4	−3·6	48	4	29·4	16·3	22·9	−1·5	19·1	—	5·6	2·91	−1·26	14	4·3	49
Victoria, B.C.	1016·5	−0·2	51	28	46·5	35·9	41·2	+0·1	38·5	93	7·3	8·41	+2·67	25	1·3	15

CLIMATOLOGICAL TABLE FOR THE BRITISH COMMONWEALTH, YEAR 1947

Stations	Pressure: Mean of day M.S.L.	Pressure: Diff. from normal	Temperatures: Absolute Max.	Temperatures: Absolute Min.	Temperatures: Mean values Max.	Temperatures: Mean values Min.	Temperatures: Mean values ½ Max. and Min.	Temperatures: Mean values Diff. from normal	Temperatures: Mean values Wet bulb	Relative humidity	Mean cloud amount	Precipitation: Total	Precipitation: Diff. from normal	Precipitation: Days	Bright Sunshine: Daily Mean	Bright Sunshine: Percentage of possible
	mb.	mb.	°F.	°F.	°F.	°F.	°F.	°F.	°F.	%	tenths	in.	in.		hr.	%
London, Kew Observatory	1015·1	+0·1	91	15	57·2	44·3	50·7	+0·3	47·2	79	7·3	19·74	−4·06	150	3·7	28
Gibraltar	1017·0	−0·9	98	40	72·4	60·1	66·3	+2·1	61·7	83	5·0	29·47	—	80	—	—
Malta	1014·9	−0·5	95	42	73·2	60·7	66·9	+0·8	62·5	65	4·1	8·99	—	63	8·8	72
St. Helena	1016·3	—	80	51	65·4	57·2	61·3	+0·6	57·5	96	9·2	41·25	+11·23	254	—	—
Freetown, Sierra Leone	1011·6	+1·8	90	69	84·1	75·3	79·7	+0·6	75·4	84	6·8	151·48	−5·75	175	6·0	49
Lagos, Nigeria ..	1011·7	+0·9	96	61	87·7	71·6	79·7	−1·0	76·9	87	8·2	69·93	—	134	4·6	38
Kaduna, Nigeria ..	1010·3	—	100	52	89·1	65·5	77·3	+0·1	66·5	55	5·9	46·23	−12·60	106	7·7	64
Chileka, Nyasaland																
Salisbury, Rhodesia																
Cape Town	1017·5	+0·5	103	36	71·6	54·9	63·2	+0·9	56·1	76	4·5	22·60	−2·44	115	—	—
Germiston, South Africa	1016·9	—	92	24	73·2	50·2	61·7	—	51·6	57	3·0	23·99	—	95	9·0	74
Mauritius	1016·1	0·0	94	55	81·3	68·1	74·6	+0·6	68·7	76	5·0	33·15	−16·60	212	8·4	69
Calcutta, Alipore Obsy.	1007·2	−0·4	108	50	89·4	72·3	80·8	+2·0	72·6	84	4·8	67·04	+2·72	123	7·0	58
Bombay	1008·4	−0·8	99	62	87·7	74·7	81·2	+0·6	73·5	81	4·6	77·09	+4·90	96	7·9	65
Madras	1008·4	−0·4	107	64	90·9	76·0	83·5	+0·4	75·0	78	5·8	34·79	−14·77	72	7·9	65
Colombo, Ceylon ..	1010·1	+0·4	92	65	86·1	75·1	80·7	−0·3	74·9	86	6·8	90·68	+10·55	173	6·9	57
Singapore	1009·1	−0·4	93	70	87·1	74·2	80·7	−0·2	77·5	84	—	121·43	+26·31	205	—	—
Hongkong	1013·3	+0·8	95	42	77·1	67·5	72·3	0·0	67·9	81	—	102·03	+16·30	178	4·8	40
Sydney, N.S.W. ..	1016·5	+0·6	94	39	70·8	56·5	63·6	+0·5	57·9	70	5·5	41·05	−6·43	137	6·9	57
Melbourne	1015·2	−1·1	103	32	68·3	50·3	59·3	+0·9	52·5	65	6·7	30·47	+5·00	163	5·3	44
Adelaide	1016·7	−0·4	105	38	71·7	53·4	62·5	−0·5	54·7	57	6·1	21·69	+0·54	145	6·3	51
Perth, W. Australia	1015·6	−0·8	100	37	73·4	54·9	64·2	0·0	57·7	61	4·5	43·42	+9·05	137	7·9	66
Coolgardie	1016·0	+0·1	106	31	77·0	52·8	64·9	+0·4	53·4	57	3·5	8·40	−1·87	60	—	—
Brisbane	1016·5	+0·6	93	40	76·4	59·2	67·8	−1·1	61·2	64	5·0	49·06	+3·77	127	7·4	62
Hobart, Tasmania	1012·3	−0·2	93	33	62·9	46·8	54·9	+0·5	49·0	66	7·1	38·61	+14·82	180	6·2	51
Wellington, N.Z. ..	1015·8	+1·1	—	32	60·4	48·2	54·3	+0·3	51·3	78	7·4	51·70	+3·66	150	5·7	47
Suva, Fiji	1011·3	0·0	92	62	82·4	72·0	77·2	+0·2	73·2	83	7·2	120·79	+3·65	235	5·4	45
Apia, Samoa ..	1010·1	−0·2	91	67	86·7	74·2	80·5	+2·0	77·2	79	6·2	127·79	+18·08	222	7·0	58
Kingston, Jamaica	1014·1	+0·4	96	65	87·9	72·7	80·3	+1·0	73·6	71	3·5	27·82	−5·77	63	8·5	70
Grenada, W. Indies	1013·1	+0·7	88	65	85·4	75·7	80·5	+1·6	76·2	79	6·8	45·74	−28·85	218	—	—
Toronto	1015·9	−0·7	93	0	35·2	39·5	47·3	+2·1	40·9	77	6·4	29·91	−1·38	129	5·3	43
Winnipeg	1015·3	−0·9	96	−29	45·7	26·0	35·9	+1·3	28·5	85	6·1	21·96	+1·78	144	5·6	45
St. John, N.B. ..	1013·9	−0·7	82	−10	50·8	35·6	43·2	+2·0	38·5	86	6·5	42·70	−5·38	156	5·4	44
Victoria, B.C. ..	1017·0	+0·3	85	5	58·3	40·9	49·6	+0·2	43·2	92	5·7	37·62	+7·31	148	6·1	50

RAINFALL OF APRIL 1948

Great Britain and Northern Ireland

County	Station	In.	Per cent of Av.	County	Station	In.	Per cent of Av.
London	Camden Square	1·68	109	*Glam.*	Cardiff, Penylan	2·64	106
Kent	Folkestone, Cherry Gdns.	1·71	103	*Pemb.*	St. Ann's Head	2·70	132
,,	Edenbridge, Falconhurst	1·42	76	*Card.*	Aberystwyth	1·71	83
Sussex	Compton, Compton Ho.	2·14	107	*Radnor*	Bir. W. W., Tyrmynydd	4·11	111
,,	Worthing, Beach Ho. Pk.	1·28	82	*Mont.*	Lake Vyrnwy	..	..
Hants	Ventnor, Roy. Nat. Hos.	1·33	79	*Mer.*	Blaenau Festiniog	4·38	71
,,	Bournemouth	1·53	85	*Carn.*	Llandudno	1·18	70
,,	Sherborne St. John	1·58	89	*Angl.*	Llanerchymedd	1·56	71
Herts.	Royston, Therfield Rec.	1·41	90	*I. Man.*	Douglas, Boro' Cem.	2·28	93
Bucks.	Slough, Upton	1·64	115	*Wigtown*	Port William, Monreith	1·73	79
Oxford	Oxford, Radcliffe	1·67	104	*Dumf.*	Dumfries, Crichton R.I.	3·56	151
N'hant.	Wellingboro', Swanspool	1·55	104	,,	Eskdalemuir Obsy.	4·41	130
Essex	Shoeburyness	1·38	114	*Roxb.*	Kelso, Floors	2·23	142
Suffolk	Campsea Ashe, High Ho.	1·33	94	*Peebles*	Stobo Castle	3·44	165
,,	Lowestoft Sec. School	1·19	80	*Berwick*	Marchmont House	1·96	97
,,	Bury St. Ed., Westley H.	1·49	97	*E. Loth.*	North Berwick Res.	1·35	96
Norfolk	Sandringham Ho. Gdns.	·81	53	*Midl'n.*	Edinburgh, Blackf'd. H.	1·48	101
Wilts.	Bishops Cannings	1·45	72	*Lanark*	Hamilton W. W., T'nhill	2·89	155
Dorset	Creech Grange	1·70	79	*Ayr*	Colmonell, Knockdolian	1·51	60
,,	Beaminster, East St.	2·18	92	,,	Glen Afton, Ayr San	3·90	130
Devon	Teignmouth, Den Gdns.	2·17	108	*Bute*	Rothesay, Ardencraig	2·80	94
,,	Cullompton	3·23	142	*Argyll*	L. Sunart, Glenborrodale	4·64	111
,,	Barnstaple, N. Dev. Ath.	2·00	94	,,	Poltalloch	2·62	87
,,	Okehampton, Uplands	3·07	96	,,	Inverary Castle	6·73	146
Cornwall	Bude School House	1·95	103	,,	Islay, Eallabus	2·77	97
,,	Penzance, Morrab Gdns.	2·87	118	,,	Tiree	2·10	85
,,	St. Austell, Trevarna	2·83	100	*Kinross*	Loch Leven Sluice	2·21	115
,,	Scilly, Tresco Abbey	2·62	134	*Fife*	Leuchars Airfield	1·42	89
Glos.	Cirencester	2·30	123	*Perth*	Loch Dhu	5·45	115
Salop.	Church Stretton	1·93	89	,,	Crieff, Strathearn Hyd.	1·40	64
,,	Cheswardine Hall	1·56	89	,,	Blair Castle Gardens	2·51	119
Staffs.	Leek, Wall Grange P.S.	1·69	82	*Angus*	Montrose, Sunnyside	1·00	55
Worcs.	Malvern, Free Library	2·07	115	*Aberd.*	Balmoral Castle Gdns.	1·55	72
Warwick	Birmingham, Edgbaston	1·96	113	,,	Dyce, Craibstone	1·52	74
Leics.	Thornton Reservoir	1·74	102	,,	Fyvie Castle	1·79	84
Lincs.	Boston, Skirbeck	1·16	86	*Moray*	Gordon Castle	1·58	90
,,	Skegness, Marine Gdns.	·91	68	*Nairn*	Nairn, Achareidh	2·37	169
Notts.	Mansfield, Carr Bank	1·53	88	*Inv's*	Loch Ness, Foyers	3·77	142
Ches.	Bidston Observatory	1·11	68	,,	Glenquoich	8·06	124
Lancs.	Manchester, Whit. Park	1·41	73	,,	Fort William, Teviot	6·64	148
,,	Stonyhurst College	2·57	95	,,	Skye, Duntuilm	3·36	103
,,	Blackpool	1·28	68	*R. & C.*	Ullapool	3·57	118
Yorks.	Wakefield, Clarence Pk.	1·51	90	,,	Applecross Gardens	4·92	144
,,	Hull, Pearson Park	2·05	131	,,	Achnashellach	8·05	150
,,	Felixkirk, Mt. St. John	1·42	85	,,	Stornoway Airfield	3·88	135
,,	York Museum	1·55	97	*Suth.*	Lairg	3·06	132
,,	Scarborough	1·07	69	,,	Loch More, Achfary	6·31	130
,,	Middlesbrough	·71	52	*Caith.*	Wick Airfield	1·62	81
,,	Baldersdale, Hury Res.	3·11	129	*Shet.*	Lerwick Observatory	3·01	131
Norl'd.	Newcastle, Leazes Pk.	1·72	108	*Ferm.*	Crom Castle	1·63	64
,,	Bellingham, High Green	2·46	114	*Armagh*	Armagh Observatory	2·50	119
,,	Lilburn Tower Gdns.	1·93	97	*Down*	Seaforde	2·03	77
Cumb.	Geltsdale	2·25	106	*Antrim*	Aldergrove Airfield	1·85	88
,,	Keswick, High Hill	2·54	83	,,	Ballymena, Harryville	1·54	58
,,	Ravenglass, The Grove	2·19	88	*Lon.*	Garvagh, Moneydig	2·26	93
Mon.	Abergavenny Larchfield	2·61	103	,,	Londonderry, Creggan	3·42	133
Glam.	Ystalyfera, Wern House	3·06	81	*Tyrone*	Omagh, Edenfel	2·34	89